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Adding IEEE 802.15.4 and 6LoWPAN to an Embedded Linux Device

FOSDEM 2017

2017-02-05, Brussels

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Agenda

- Motivation
- Linux-wpan Project
- Hardware
- Configuration
- Communication with RIOT and Contiki

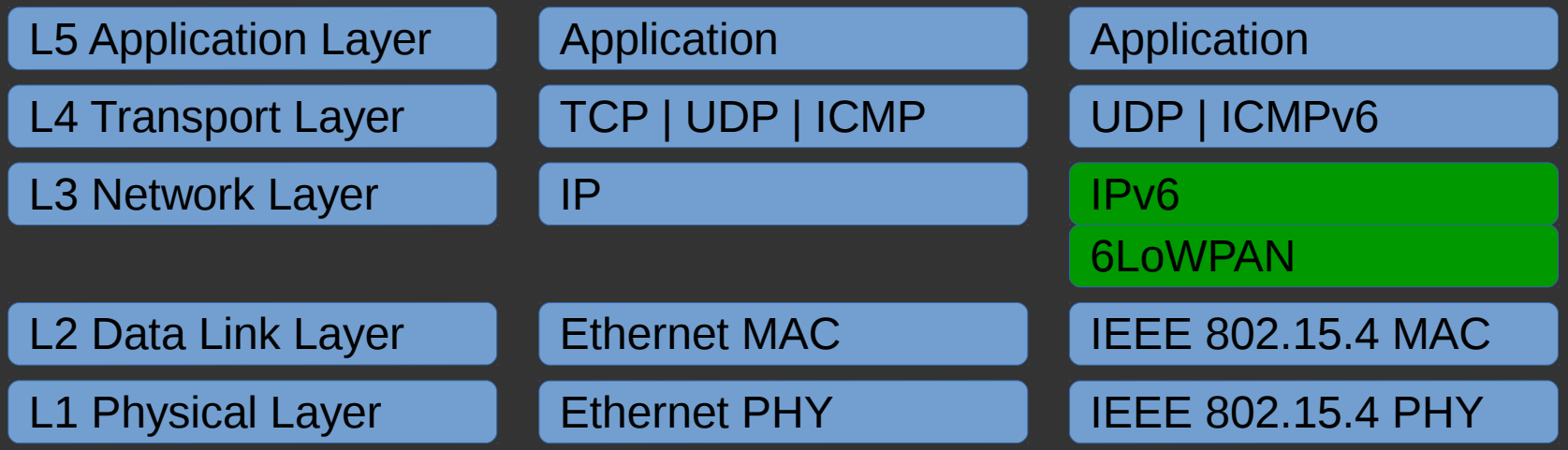
Motivation

IEEE 802.15.4

- IEEE specifications for Low-Rate Wireless ~~Personal Area~~ Networks
- Not only low-rate, but also low-power
- Designed for small sensors to run months/years on battery with the right duty cycle
- 127 bytes MTU and 250 kbit/s
- Sometimes confused with ZigBee as it is used as PHY and MAC layer there

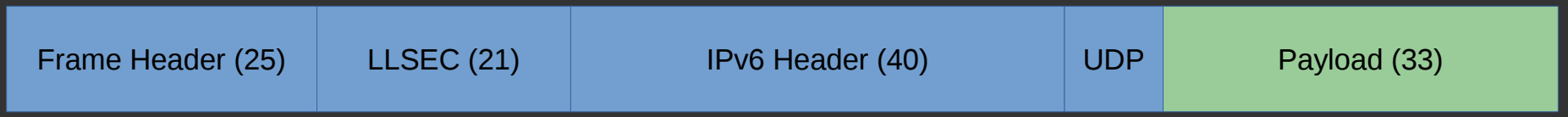
6LoWPAN

- Physical and MAC layer defined by IEEE 802.15.4 from 2003 onwards (latest update from 2015)
- Series of IETF specifications from 2007 onwards (RFCs 4944, 6282, etc)



The Header Size Problem

- Worst-case scenario calculations
- Maximum frame size in IEEE 802.15.4: 127 bytes
- Reduced by the max. frame header (25 bytes): 102 bytes
- Reduced by highest link-layer security (21 bytes): 81 bytes
- Reduced by standard IPv6 header (40 bytes): 41 bytes
- Reduced by standard UDP header (8 bytes): 33 bytes
- This leaves only **33 bytes** for actual payload
- The rest of the space is used by headers (~ 3:1 ratio)



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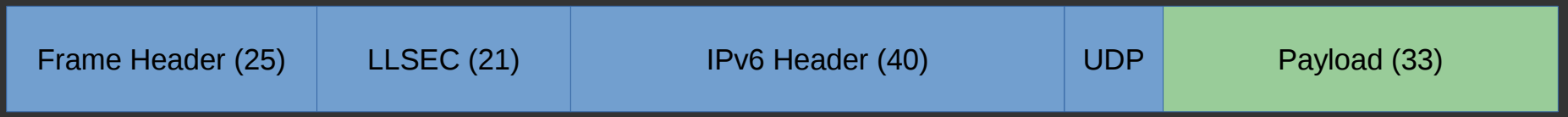
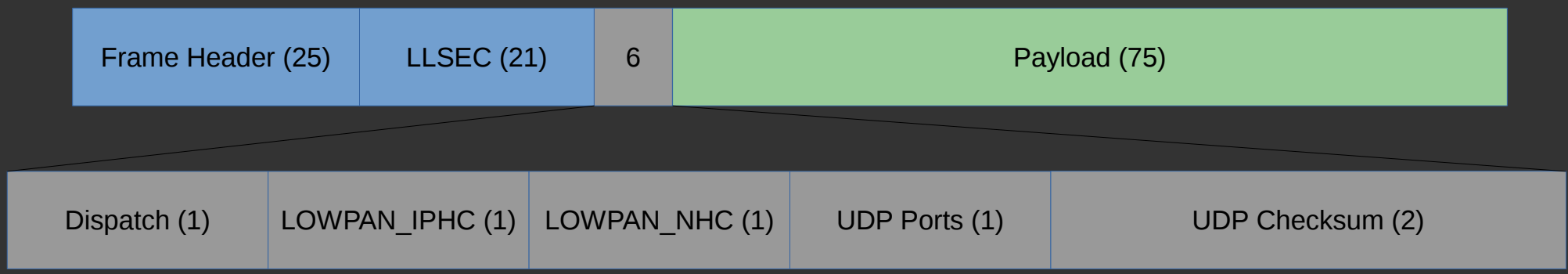


The Header Size Solution

- IPv6 with link-local and UDP on top
- IPHC with NHC for UDP
- The 48 bytes IPv6 + UDP header could in the best cases be reduced to 6 bytes
- That allows for a payload of **75 bytes** (~ 2:3 ratio)



Linux-wpan

- Platforms already running Linux would benefit from native IEEE 802.15.4 and 6LoWPAN subsystems
- IEEE 802.15.4 transceivers can easily be added to existing hardware designs
- Battery powered sensors on the other hand are more likely to run an OS like RIOT or Contiki
- Example 1: Google OnHub AP which already comes with, de-activated, IEEE 802.15.4 hardware
- Example 2: Ci40 Creator board as home IoT hub

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Linux-wpan Project

Linux-wpan Project

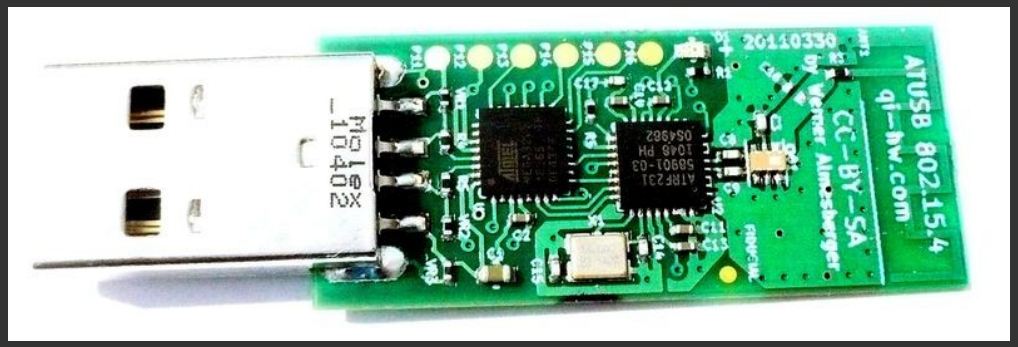
- IEEE 802.15.4 and 6LoWPAN support in mainline
- Started in 2008 as linux-zigbee project, from 2012 mainline
- New project name to avoid confusion: linux-wpan
- Normal kernel development model
- Patches are posted and reviewed on the mailing list
- Small community: 2 core devs and ~4 additional people for specific drivers
- Linux-wpan mailing list (~93 people), IRC (~29 people)

Current Status

- ieee802154 layer with softMAC driver for various transceivers
- 6LoWPAN with fragmentation and reassembly (RFC 4944)
- Header compression with IPHC and NHC for UDP (RFC 6282), shared with Bluetooth subsystem
- Link Layer Security
- Testing between Linux, RIOT and Contiki
- Mainline 4.1 onwards recommended
- Active development, newer is better :-)

Development Boards

- MIPS based Ci40 Creator (CA-8210)
- Raspberry Pi with Openlabs shield (AT86RF233)
- Transceivers can be hooked up via SPI
  (all drivers have devicetree bindings)
- ATUSB dongle



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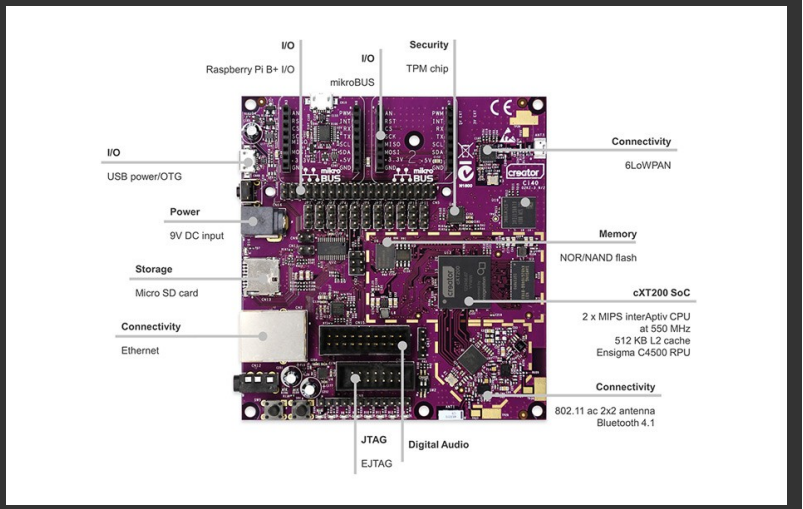

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Hardware

Hardware Requirements

- Free SPI port
- Some additional free GPIO pins
- You can choose between off the shelf modules or adding it directly to your design
- Alternatively you could use USB

Devicetree Bindings

- Boards need devicetree support
- All our drivers have bindings
- Example for the at86rf233:

```
&spi {
    status = "okay";
    at86rf233@0 {
        compatible = "atmel,at86rf233";
        spi-max-frequency = <6000000>;
        reg = <0>;
        interrupts = <23 4>;
        interrupt-parent = <&gpio>;
        reset-gpio = <&gpio 24 1>;
        sleep-gpio = <&gpio 25 1>;
        xtal-trim = /bits/ 8 <0x0F>;
    };
};
```

Hardware Support

- Mainline drivers for at86rf2xx, mrf24j40, cc2520, atusb and adf7242
- Pending driver for ca-8210
- Old out of tree driver for Xbee
- ATUSB dongle to be used on your workstation

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Transceiver Comparison

Chipset	Interface	Driver	2.4 GHz	Sub GHz	ARET	IEEE specs
ADF7242	SPI or PMOD	✔	✔	✘	✔	2003-2006
AT86RF212	SPI + GPIO	✔	✘	✔	✔	2003-2006
AT86RF212b	SPI + GPIO	✔	✘	✔	✔	2003-2011
AT86RF215	SPI + GPIO + LVDS	✘	✔	✔	✔	2003-2011, 15.4g
AT86RF230	SPI + GPIO	✘	✔	✘	✔	2003
AT86RF231	SPI + GPIO	✔	✔	✘	✔	2003-2006
AT86RF233	SPI + GPIO	✔	✔	✘	✔	2003-2011
ATUSB (AT86RF231)	USB	✔	✔	✘	✔	2003-2006
RZUSB (AT86RF230)	USB	✔	✔	✘	✔*	2003
CA8210	SPI + GPIO	✔*	✔	✘	✔	2003-2006
CC2420	SPI + GPIO	✘	✔	✘	✘	2003
CC2520	SPI + GPIO	✔	✔	✘	✘	2003-2006
CC2531	USB	✘	✔	✘	✘*	2003-2006
MRF24J40	SPI + GPIO	✔	✔	✘	✔	2003
XBee	UART	✘*	✔	✘	✔	2003??

Virtual Driver

- Fake loopback driver (similar to hwsim of wireless)
- Great for testing
- Support for RIOT and OpenThread to use this when running as native Linux process
- Will help interoperation testing between the different network stacks in an virtual environment

  $ modprobe fakelb numlbs=4

  $ Configure for Linux, RIOT, OpenThread and monitor

Configuration

Wpan-tools: iwpan

- Userspace configuration utility
- Netlink interface ideas as well as code borrowed from the iw utility
- Used to configure PHY and MAC layer parameters
- Including: channel, PAN ID, power settings, short address, frame retries, etc
- Packaged by some distributions (Fedora and Debian up to date, Ubuntu on 0.5, OpenSUSE, Gentoo, Arch, etc missing)

Wpan-tools: wpan-ping

- Ping utility on the IEEE 802.15.4 layer
- Not a full ICMP ping replacement, but good enough for some basic testing and measurements

```
# run on server side
$ wpan-ping –-daemon
# run on client side
$ wpan-ping –-count 100 –-extended –-address
 00:11:22:33:44:55:66:77
```

Interface Bringup

- The wpan0 interface shows up automatically
- Setting up the basic parameters:

```
$ ip link set lowpan0 down
$ ip link set wpan0 down
$ iwpan dev wpan0 set pan_id 0xabcd
$ iwpan phy phy0 set channel 0 26
$ ip link add link wpan0 name lowpan0 type lowpan
$ ip link set wpan0 up
$ ip link set lowpan0 up
```

Monitoring

- Setting up the interface in promiscuous mode:

  $ iwpan dev wpan0 del

  $ iwpan phy phy0 interface add monitor%d type monitor

  $ iwpan phy phy0 set channel 0 26

  $ ip link set monitor0 up

  $ wireshark -i monitor0

- No automatic channel hopping (you can change the channel manually in the background)

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Communication with RIOT & Contiki

RIOT

- “The friendly Operating System for the Internet of Things” (LGPL)
- Testing against Linux-wpan is part of the release testing process for RIOT
- Active developer discussions and bug fixing between projects

Contiki

- “The Open Source OS for the Internet of Things” (BSD)
- Very fragmented project
- Sadly many forks for academic or commercial purpose which have a hard time to get merged
- Still an important role as IoT OS for tiny devices

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Comparison

Feature	Linux	RIOT	Contiki
IEEE 802.15.4: data and ACK frames	✔	✔	✔
IEEE 802.15.4: beacon and MAC command frames	✘	✘	✘
IEEE 802.15.4: scanning, joining, PAN coordinator	✘	✘	✘
IEEE 802.15.4: link layer security	✔	✘	✔
6LoWPAN: frame encapsulation, fragmentation, addressing (RFC 4944)	✔	✔	✔
6LoWPAN: IP header compression (RFC 6282)	✔	✔	✔
6LoWPAN: next header compression, UDP only (RFC 6282)	✔	✔	✔
6LoWPAN: generic header compression (RFC 7400)	✘	✘	✘
6LoWPAN: neighbour discovery optimizations (RFC 6775)	Partial	✔	✘
RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks	✔	✔	✔
Mesh link establishment draft	✘	✘	✘

Others

- mbed OS from ARM: network stack is closed source, so nothing to test against
- Zephyr: new network stack not tested yet
- OpenThread: Open Source implementation of the Thread protocol

Future

Linux-wpan Future

- Implement missing parts of the IEEE 802.15.4 specification
  - Beacon and MAC command frame support
  - Coordinator support in MAC layer and wpan-tools
  - Scanning
- Add better support for HardMAC transceivers
- Neighbour Discovery Optimizations (RFC 6775), started
- Evaluate running OpenThread on top of linux-wpan
- Configuration interface for various header compression modules
- Expose information for route-over and mesh-under protocols

Summary

Take away

- Running an IEEE 802.15.4 wireless network under Linux is not hard
- Tooling and kernel support is already there
- Border router scenario most likely use case but nodes or routers also possible

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Thank you!

http://www.slideshare.net/SamsungOSG

References

- IEEE 802.15.4 specification (PHY and MAC layer)
  http://standards.ieee.org/about/get/802/802.15.html
- RFC 4944: Transmission of IPv6 Packets over IEEE 802.15.4 Networks
  https://tools.ietf.org/html/rfc4944
- RFC 6282: Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks
  https://tools.ietf.org/html/rfc6282
- RFC 7400: 6LoWPAN-GHC: Generic Header Compression for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)
  https://tools.ietf.org/html/rfc7400
- Linux-wpan source and project pages
  https://github.com/linux-wpan
  http://wpan.cakelab.org/

6LoWPAN Fragmentation

- IPv6 requires the link to allow for a MTU of at least 1280 bytes
- This is impossible to handle in the 127 bytes MTU of IEEE 802.15.4
- 6LoWPAN 11 bit fragmentation header allows for 2048 bytes packet size with fragmentation
- But fragmentation can still lead to bad performance in lossy networks, best to avoid it in the first place

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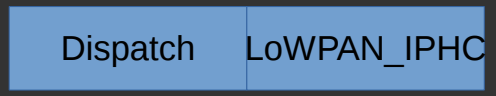
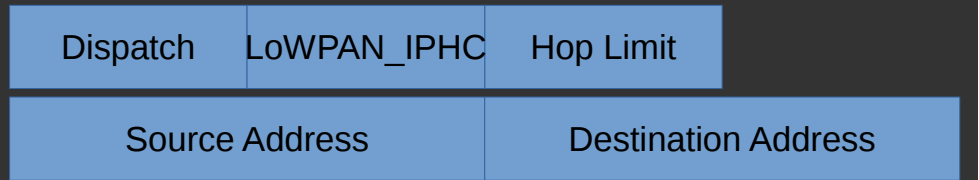
IPv6 Header Compression (IPHC)

- Defining some default values in IPv6 header
  - Version == 6, traffic class & flow-label == 0, hop-limit only well-known values (1, 64, 255)
  - Remove the payload length (available in 6LoWPAN fragment header or data-link header)
- IPv6 stateless address auto configuration based on L2 address
  - Omit the IPv6 prefix (global known by network, link-local defined by compression (FE80::/64)
  - Extended: EUI-64 L2 address use as is
  - Short: pseudo 48 bit address based short address: PAN_ID:16 bit zero:SHORT_ADDRESS

6LoWPAN Header IPHC link-local (2 bytes)



6LoWPAN Header IPHC multi-hop (7 bytes)



Next Header Compression

- NHC IPv6 Extension Header compression (RFC6282)
  - Hop-by-Hop, Routing Header, Fragment Header, Destination Options Header, Mobility Header
- NHC UDP Header compression (RFC6282)
  - Compressing ports range to 4 bits
  - Allows to omit the UDP checksum for cases where upper layers handle message integrity checks
- GHC: LZ-77 style compression with byte codes (RFC7400)
  - Appending zeroes, back referencing to a static dictionary and copy
  - Useful for DTLS or RPL (addresses elided from dictionary)

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Link Layer Security

Link Layer Security

- Specified by IEEE 802.15.4
- It defines confidentiality (AES-CTR), integrity (AES CBC-MAC) and encryption and authentication (AES CCM) security suites
- Key handling, key exchange, roll over, etc is not defined
- Tested Linux against Linux and Contiki 3.0
- No way to test against RIOT as they have no LLSEC support right now

LLSEC Linux-wpan

- Needs the llsec branch in wpan-tools for configuration
- CONFIG_IEEE802154_NL802154_EXPERIMENTAL

```
$ iwpan dev wpan0 set security 1

$ iwpan dev wpan0 key add 2 $KEY 0 $PANID 3 $EXTADDR

$ iwpan dev wpan0 seclevel add 0xff 2 0

$ iwpan dev wpan0 device add 0 $PANID $SHORTADDR $EXTADDR 0
0
```

LLSEC Contiki 3.0

- You need the following Contiki build options configured in your project-conf.h to make use of LLSEC with network wide key:

```
#define NETSTACK_CONF_LLSEC noncoresec_driver
#define LLSEC802154_CONF_SECURITY_LEVEL FRAME802154_SECURITY_LEVEL_ENC_MIC_32

#define NONCORESEC_CONF_KEY {   \
0x00, 0x01, 0x02, 0x03, \
0x04, 0x05, 0x06, 0x07, \
0x08, 0x09, 0x0A, 0x0B, \
0x0C, 0x0D, 0x0E, 0x0F, \
}
```